Three-Dimensional Material Properties of Composites with S2-Glass Fibers or Ductile Hybrid Fabric

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ABSTRACT

Material properties were determined for fiber-reinforced polymers (FRPs) with respect to all three material orientations using existing ASTM standards when applicable. The in-plane and out-of-plane material properties include; shear strength, shear modulus, compressive strength, compressive modulus, tensile strength, tensile modulus, and Poisson's ratio. Parameters included in this study include the resin and fiber composition, the nominal thickness of the composite plate, and the test temperature. The three material compositions were; (1) Huntsman PolyUrethane (PU) Rencast 6405 with S-2 Glass fibers, (2) Applied Poleramic (API) SC-15 Epoxy with S-2 Glass fibers, and (3) Huntsman PU Rencast 6405 with Ductile Hybrid Fabric. The nominal thickness were; 1.91 cm., 2.54 cm., and 3.81 cm. The nominal test temperatures were; -40 °C, 21 °C (ambient), and 60 °C.

The material testing results indicate that all strength and stiffness properties, both in-plane and out-of-plane, decrease with an increase in test temperature. The strength of materials with API SC-15 epoxy is higher than the strength results of materials with Huntsman PU Recast 6405. However, the in-plane stiffness of the material with Ductile Hybrid Fabric was higher than other materials. The strength and stiffness properties of materials with Huntsman PU Rencast 6405 are much more influenced by temperature than materials with API SC-15 epoxy. The strength and stiffness properties of composite materials are not significantly influenced by the material thickness. The Poisson's ratio is not directly influenced by temperature or material thickness.

1. INTRODUCTION AND BACKGROUND

The United States Army Tank Automotive Research Development and Engineering Center (TARDEC) funded a research project to determine the mechanical properties of seven fiber reinforced polymer materials with three material compositions. The primary objective of this research was to determine the strength and stiffness (tension, compression, and shear) of new innovative composites in all three material orientations and under a range of temperatures.

Details in regards to the fabrication of specimens and testing procedure were presented elsewhere [1]. In general, in-plane properties were determined using available ASTM standards with some modifications as necessary. Out-of-plane properties were measured using ASTM standards when available. However, some new standards were developed as required.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE
13 JAN 2013

2. REPORT TYPE
Journal Article

3. DATES COVERED
14-07-2012 to 10-11-2012

4. TITLE AND SUBTITLE
Three-Dimensional Material Properties of Composites with S2-Glass Fibers or Ductile Hybrid Fabric

5a. CONTRACT NUMBER
W56HZV-08-C-0236

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Keith Kowalkowski; Nabil Grace; Scott Hodges

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Lawrence Technological University,21000 West Ten Mile Road,Southfield,Mi,48075-1058

8. PERFORMING ORGANIZATION REPORT NUMBER
; #23597

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000

10. SPONSOR/MONITOR’S ACRONYM(S)
TARDEC

11. SPONSOR/MONITOR’S REPORT NUMBER(S)
#23597

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Public Release**	**18**	

Fiber-based composites are used more and more frequently for several applications in the military, the construction industry, the transportation industry, and other industries. Fiber reinforced composites are favorable for vehicle components since they are lightweight with favorable strength and stiffness properties. Of current interest to the US military is the performance of new innovative composites under a wide range of temperatures.

S-2 glass/SC-15 epoxy resin is a material that is currently of high interest to the US military. It is a well-established benchmark as an impact resistant material [2]. Applied Poleramic Inc. (API) SC-15 rubber toughened epoxy resin has shown to have low viscosity and high toughness relative to other epoxy systems. SC-15 is the most widely data based Vartm/Scrimp matrix resin which includes uses in the Army, at the University of Delaware, and several Phase II SBIR's for ballistic panels [3]. However, limited strength and stiffness properties in regards to the S-2 glass/SC-15 epoxy resin are found in the literature [4].

Traditionally, the fibers within composite materials are oriented along two axes designating a plane associated with the fibers. In design, the composite systems are oriented such that the fibers resist the applied loads. Normal stresses that develop from axial loads and moments are distributed to and therefore resisted by both the fibers and the resin. The through thickness (“out-of-plane”) mechanical properties are often not influential in the design. In tension, the load is primarily resisted by the strength of the resin [1]. Therefore, the properties of composites through the thickness are often neglected and test standards need to be developed.

2. EXPERIMENTAL PROGRAM

The experimental program included seven materials with three different compositions of fibers and resin. Table 1 summarizes the characteristics of the different materials including the fibers and resin system as well as the nominal composite panel thickness when fabricated. The volume fraction (V_f) and the void volume (V_v) were determined using ASTM D3171-09 [6]. From this standard, Method 1, Procedure G (Ignition) was used.

Table 1. Material Test Matrix

Material	**Resin**	**Fiber(s)**	**Fiber Orientation**	**Nominal Thickness**	**Volume Fraction (V_f)**	**Void Volume (V_v)**
Material 1	Huntsman PolyUrethane (PU) Rencast 6405	S2-Glass Plain Weave (PW) 24oz./yd.^{2}	0/90, 45/-45	3.8 cm.	43.4%	11.9%
Material 2	Applied Poleramic (API) SC-15 Epoxy	S2-Glass Plain Weave (PW) 24oz./yd.^{2}	0/90, 45/-45	3.8 cm.	43.2%	5.8%
Material 3	Huntsman PolyUrethane (PU) Rencast 6405	S2-Glass Plain Weave (PW) 24oz./yd.^{2}	0/90, 45/-45	2.5 cm.	44.9%	8.3%
Material 4	Huntsman PolyUrethane (PU) Rencast 6405	S2-Glass Plain Weave (PW) 24oz./yd.^{2}	0/90, 45/-45	1.9 cm.	43.5%	5.6%
Material 5	Applied Poleramic (API) SC-15 Epoxy	S2-Glass Plain Weave (PW) 24oz./yd.^{2}	0/90, 45/-45	1.9 cm.	46.1%	9.6%
Material 6	Applied Poleramic (API) SC-15 Epoxy	S-2Glass Plain Weave (PW) 24oz./yd.^{2}	0/90, 45/-45	2.5 cm.	43.7%	6.9%
Material 7	Huntsman PolyUrethane (PU) Rencast 6405	Ductile Hybrid Fabric (DHF)	0, 45, -45	1.9 cm.	49.9%	1.0%

Although only three different compositions were considered, some materials with the same compositions had varying thickness. Materials 1 and 2 were 3.81 cm. thick. Materials 3 and 5 were 2.54 cm. thick. Materials 4, 6, and 7 were 1.91 cm. thick. From Table 1, no significant differences were identified in either the fiber volume fraction or the void volume for three materials with the same composition. The void content of Material 1 was noticeably higher.

As listed, Material 7 was reinforced with ductile hybrid fabric (DHF) [7]. DHF is a uniaxial ductile fiber-reinforced polymer. It consists of two types of carbon fibers and one type of glass fiber. It was developed to provide a pseudo-ductile behavior with a low yield-equivalent strain value in tension primarily for the strengthening of reinforced concrete beams and columns. For this material, the fiber volume fraction and void volume is estimated as an estimated weighted average of the three different fibers was calculated for fiber density.

The vacuum assisted resin transfer molding (VARTM) process was used to manufacture the composite plates for each specimen. For panels infused with API SC-15 resin, the panel dimensions were 76.2 cm. x 76.2 cm. and were infused from one side to the other. The 3.81 cm. and 2.54 cm. thick panels had an additional line port at the center of the panel that was added once the resin had injected past the midpoint. Since the resin flow is not uniform across the panel, the flow of resin on the bottom (the slowest) was used to determine when the resin had crossed the midpoint. The part was cured overnight at room temperature and then post cured at 93 °C as prescribed by the manufacturer. The oven was cooled to 38 °C and then allowed to cool gradually.

A similar procedure was used to manufacture the panels with Huntsman Rencast 6405. However, the panel sizes were 30.5 cm. x 61 cm. since the resin has a considerably shorter working time. The smaller panel size was adequate for all thicknesses and allowed for an adequate amount of time for the panel to be completely infused. The cure cycle for this resin was performed at room temperature for a total of seven days before the panel was used as prescribed by the manufacturer.

Table 2 provides the test matrix which identifies 7 "test types" and the material properties each test type measures. In Table 2, '*E*' represents the elastic modulus when subjected to tensile stresses and '*EC*' represents the elastic modulus when subjected to compressive stresses. '*ν*' represents the Poisson's ratio when subjected to tension stresses and '*νC*' represents the Poisson's ratio when subjected to compressive stresses. '*ST*' represents tensile strength, '*SC*' represents compressive strength, and '*S*' represents shear strength. For each material and each test type, all material properties were measured at three different temperatures of -40 °C, 21 °C (ambient), and 60 °C. Table 2 also lists the ASTM standard that was followed in order to perform the tests. Further information about performing each test type is presented elsewhere [1].

Table 2. Test Types with Measured Material Properties

Test Type	Elastic Properties	Strength Properties	ASTM Ref.
In-Plane Tension	E_x, E_y, ν_{xy}	ST_x, ST_y	D 3039 [8]
In-Plane Compression	EC_x, EC_y, νC_{xy}	SC_x, SC_y	D 6641 [9]
In-Plane Shear	G_{xy}	S_{xy}	D 7078 [10]
Out-of-Plane Tension	E_z	ST_z	D 7291 [11]
Out-of-Plane Compression	EC_z	SC_z	-
Out-of-Plane Shear	G_{yz}, G_{xz}	S_{yz}, S_{xz}	D 5379 [12]
Out-of-Plane Poisson	ν_{yz}, ν_{xz}	-	-

3. EXPERIMENTAL RESULTS

This section summarizes the material testing results. The results are discussed in more detail in Sections 4, 5, and 6. Table 3 shows the results of Materials 1, 3, and 4. All three of these materials have a material composition that consists of Huntsman PU Rencast 6405 and S-2 glass. For each material, each test type, and each test temperature, the testing was complete when relatively consistent and reliable results were measured for five specimens. The results presented in Table 3 are mean values from the results of the five specimens tested under the same test temperature. A majority of the composites tested are quasi-isotropic with fibers oriented 90° from each other. The properties with respect to the 'x' and 'y' directions are assumed identical.

Table 3. Material Property Results for Materials with Huntsman PU Rencast 6405 and S-2 Glass

Test	**Property**	**Material 1 (t = 3.81 cm)**			**Material 3 (t = 2.54 cm)**			**Material 4 (t = 1.91 cm)**		
		-40 °C	**21 °C**	**60 °C**	**-40 °C**	**21 °C**	**60 °C**	**-40 °C**	**21 °C**	**60 °C**
In-Plane Tension	ST_x, ST_y (MPa)	375	312	220	352.8	312	234	315	298	214
	E_x, E_y (MPa)	15765	13696	11422	15345	14043	10539	14486	12301	11473
	ν_{xy}	0.189	0.211	0.177	0.267	0.249	0.268	0.216	0.248	0.428
In-Plane Compression	SC_x, SC_y (MPa)	258	172	88	270	182	82	254	184	72
	EC_x, EC_y (MPa)	18563	18740	16135	19841	19279	15846	19581	18827	15473
	νC_{xy}	0.290	0.297	0.279	0.253	0.262	0.298	0.246	0.206	0.297
In-Plane Shear	S_{xy} (MPa)	163	150	122	212	163	104	195	132	71
	G_{xy} (MPa)	8560	8829	5834	9411	9212	7130	9075	8708	6278
Out-of-Plane Tension	ST_z (MPa)	34.3	25.0	13.1	31.7	21.3	13.1	30.8	22.8	11.0
	E_z (MPa)	8986	7429	1592	7865	6420	2308	7734	6796	1825
Out-of-Plane Compression	SC_z (MPa)	452	386	320	493	398	348	480	357	335
	EC_z (MPa)	8037	7090	6683	8489	7446	8094	7632	5547	6179
Out-of-Plane Shear	S_{xz}, S_{yz} (MPa)	37.0	21.1	7.3	31.8	18.7	6.4	32.9	20.1	7.0
	G_{xz}, G_{yz} (MPa)	2719	1880	138	4150	3177	134	4162	3153	301
OP Poisson	ν_{xz}, ν_{yz}	0.113	0.132	-0.037	0.179	0.137	0.118	0.153	0.174	0.132

The results of Materials 2, 5, and 6 are shown in Table 4. All three of these materials have a material composition that consists of API SC-15 and S-2 glass. The results once again represent the average results of five specimens tested.

Table 4. Material Property Results for Materials with API SC-15 and S-2 Glass

Test	Property	Material 2 (t = 3.81 cm)			Material 5 (t = 2.54 cm)			Material 6 (t = 1.91 cm)		
		-40 °C	21 °C	60 °C	-40 °C	21 °C	60 °C	-40 °C	21 °C	60 °C
In-Plane Tension	ST_x, ST_y (MPa)	357	331	291	371	339	298	323	314	263
	E_x, E_y (MPa)	16544	14951	15035	17877	16057	15468	15922	13918	13174
	ν_{xy}	0.250	0.213	0.267	0.257	0.218	0.277	0.242	0.264	0.216
In-Plane Compression	SC_x, SC_y (MPa)	316	278	229	301	242	211	311	225	180
	EC_x, EC_y (MPa)	19732	19795	18567	20394	20759	19232	20669	19933	18357
	νC_{xy}	0.312	0.325	0.319	0.263	0.257	0.250	0.261	0.256	0.276
In-Plane Shear	S_{xy} (MPa)	259	214	192	262	217	175	255	198	157
	G_{xy} (MPa)	9856	9058	8424	12931	10673	10396	10455	9845	9048
Out-of-Plane Tension	ST_z (MPa)	34.6	30.0	26.8	9.4	10.2	8.4	30.8	27.2	23.5
	E_z (MPa)	10101	9821	7630	11302	11056	8906	8774	8608	7133
Out-of-Plane Compression	SC_z (MPa)	692	554	455	696	551	492	761	611	536
	EC_z (MPa)	13251	9809	8502	12626	9276	10065	9722	8171	8003
Out-of-Plane Shear	S_{xz}, S_{yz} (MPa)	31.5	26.2	21.3	26.8	27.0	20.8	33.4	29.0	25.3
	G_{xz}, G_{yz} (MPa)	5774	5958	4828	8016	7206	5375	3235	2350	2115
OP Poisson	ν_{xz}, ν_{yz}	0.170	0.185	0.119	0.154	0.144	0.147	0.130	0.171	0.099

Table 5 shows the results of Material 7 which indicated different ν_{xz} and ν_{yz} values. Information about the material orientations associated with these measurements is provided elsewhere [13].

Table 5. Material Property Results for Material with Huntsman PU Rencast 6405 and DHF

Test	Property	Material 7		
		-40 °C	21 °C	60 °C
In-Plane Tension	ST_x, ST_y (MPa)	411	310	244
	E_x, E_y (MPa)	45721	46971	39069
	ν_{xy}	0.562	0.623	0.888
In-Plane Compression	SC_x, SC_y (MPa)	287	190	89
	EC_x, EC_y (MPa)	30115	37746	38568
	νC_{xy}	0.360	0.388	0.400
In-Plane Shear	S_{xy} (MPa)	166	128	81
	G_{xy} (MPa)	13316	13473	10811
Out-of-Plane Tensile	ST_z (MPa)	22.1	21.9	11.0
	E_z (MPa)	7484	6728	2556
Out-of-Plane Compression	SC_z (MPa)	321	242	186
	EC_z (MPa)	7456	6448	5511
Out-of-Plane Shear	S_{xz}, S_{yz} (MPa)	34.8	23.4	9.8
	G_{xz}, G_{yz} (MPa)	2498	1889	549
OP Poisson	ν_{xz}	0.052	0.002	-0.082
	ν_{yz}	0.208	0.268	0.321

4. INFLUENCE OF TEMPERATURE ON EXPERIMENTAL RESULTS

Tables 3, 4, and 5 indicate the strength and stiffness of composite materials decreases as the test temperature increases. This trend is noticeable when comparing the experimental results at a test temperature of -40 °C to the results at 21 °C and when comparing the results at 21 °C to the results at 60 °C. In addition, the results indicate that materials with API SC-15 epoxy are more comparable at high and ambient temperatures than materials with Huntsman PU Rencast 6405. Usually, composite materials will be selected or designed using their material properties measured at ambient temperatures. There is not a concern in regards to the increase in strength and stiffness at a temperature of -40 °C. Therefore, the discussion presented herein focuses on high temperature results in comparison to ambient temperature results. To illustrate the influence of temperature on material properties, normalized figures are presented. The material testing results at all three temperatures are normalized to the material testing results at an ambient temperature of 21 °C. The values corresponding to 21 °C are always equal to 1.0.

Figure 1 shows the normalized in-plane tensile strength (ST_x, ST_y) results. The results indicate that the in-plane tensile strength consistently decreases with an increase in temperature. Overall, the tensile strength of all materials with Huntsman PU Rencast 6405 is more significantly influenced by temperature. For materials with API SC-15 epoxy, the tensile strength decreases by as much as 16% at a temperature of 60 °C (Material 6). For materials with Rencast 6405, the tensile strength decreases by as much as 31% (Material 1).

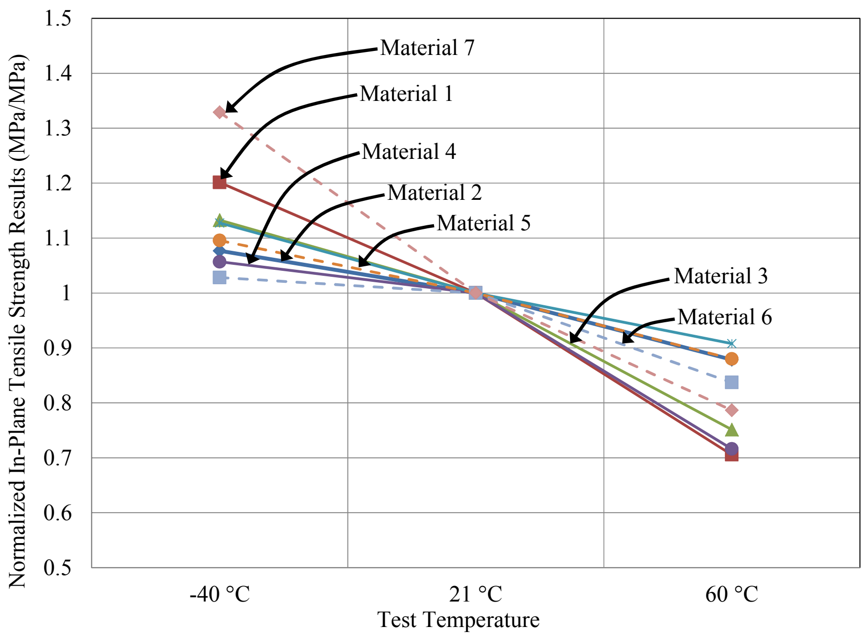

Figure 1. Effects of Test Temperature on In-Plane Tensile Strength (ST_x, ST_y)

The influence of temperature on the in-plane tensile strength presented in Figure 1 was similar to the influence of temperature on the in-plane compressive and shear strengths. For materials with Huntsman Rencast 6405 and at a temperature of 60 °C, the in-plane compressive strength decreases to as low as 39% that at ambient (Material 4) and the in-plane shear strength decreases to as low as 54% that at ambient (Material 4). For materials with API SC-15 epoxy, the in-plane

shear and compressive strength at a temperature of 60 °C were found to usually be within 20% that at ambient.

Figure 2 shows the normalized out-of-plane tensile strength (ST_x) results. Although the results are more irregular than the in-plane results, they usually indicate that the out-of-plane tensile strength decreases with an increase in temperature. For Material 5, the out-of-plane tension strength was lower at -40 °C. The out-of-plane tension strengths for materials with SC-15 epoxy at hot and cold temperatures are always within 20% that at ambient temperatures. However, the out-of-plane tensile strength for materials with Huntsman Rencast 6405 at -40 °C is as much as 50% higher than at ambient and the strength at 60 °C is as much as 50% lower than at ambient.

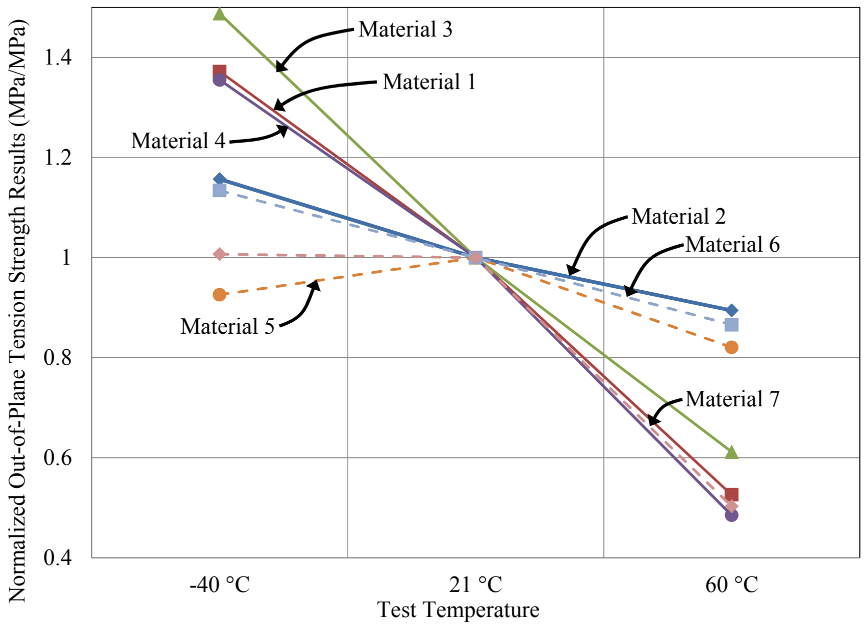

Figure 2. Effects of Temperature on the Out-of-Plane Tensile Strength (ST_x)

The influence of temperature on the out-of-plane shear strength was found to be very similar to the influence of temperature on the out-of-plane tensile strength. However, temperature has a smaller influence on the out-of-plane compressive strength. The out-of-plane compressive strengths for all materials at 60 °C are always within 25% that at ambient.

Figure 3 shows the normalized in-plane tensile elastic modulus (E_x, E_y) results. The results indicate that the in-plane tensile modulus is not influenced by temperature as significantly as the in-plane tensile strength (ref. Figure 1). The results at -40 °C and 60 °C are generally within 20% that at ambient temperatures. The in-plane tensile modulus of materials with Huntsman PU Rencast 6405 is influenced more by elevated temperatures.

The influence of temperature on the in-plane compressive elastic modulus (ECx, ECy) and the in-plane shear modulus (G_{xy}) was found similar to the influence of temperature on the in-plane tensile elastic modulus. All in-plane compressive modulus results at -40 °C and 60 °C were within 20% of that at ambient temperatures. The trends in the results indicate that the in-plane shear modulus increases with a decrease in temperature. However, the shear modulus decreased for two materials at a temperature of -40 °C. The in-plane shear modulus at -40 °C and 60 °C

was always within 20% that at ambient for materials with API SC-15 epoxy and S-2 glass. For other materials, the differences were as high as 35%.

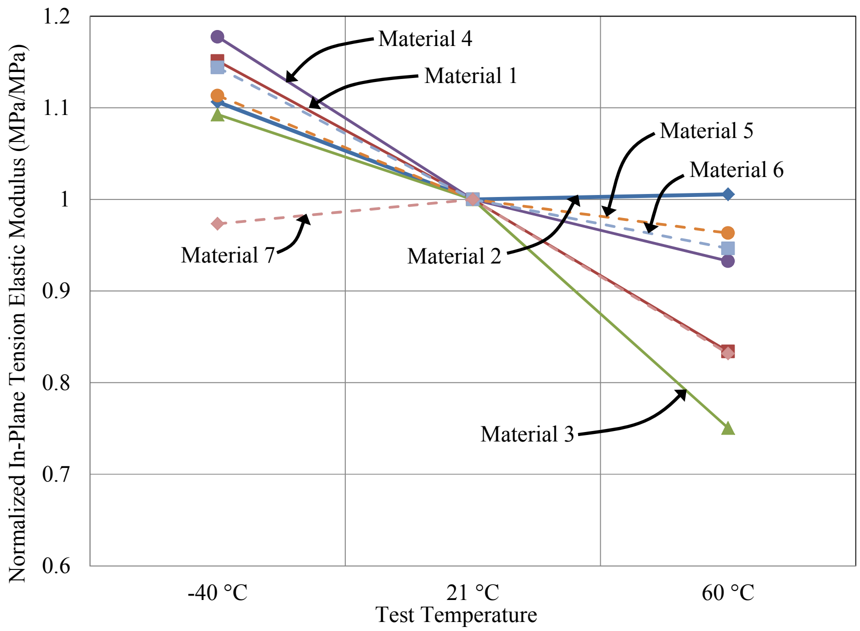

Figure 3. Effects of Temperature on In-Plane Tensile Elastic Modulus

Figure 4 shows the normalized out-of-plane tensile elastic modulus (E_z) results indicating that the out-of-plane tensile modulus increases with a decrease in temperature. For all materials with API SC-15 epoxy and S-2 glass, the results at -40 °C are comparable to the results at ambient and the results at 60 °C are within 21% of that at ambient. The influence of temperature is significant for materials with Huntsman PU Rencast 6405. The out-of-plane tension decreases by as much as 79% at a temperature of 60 °C.

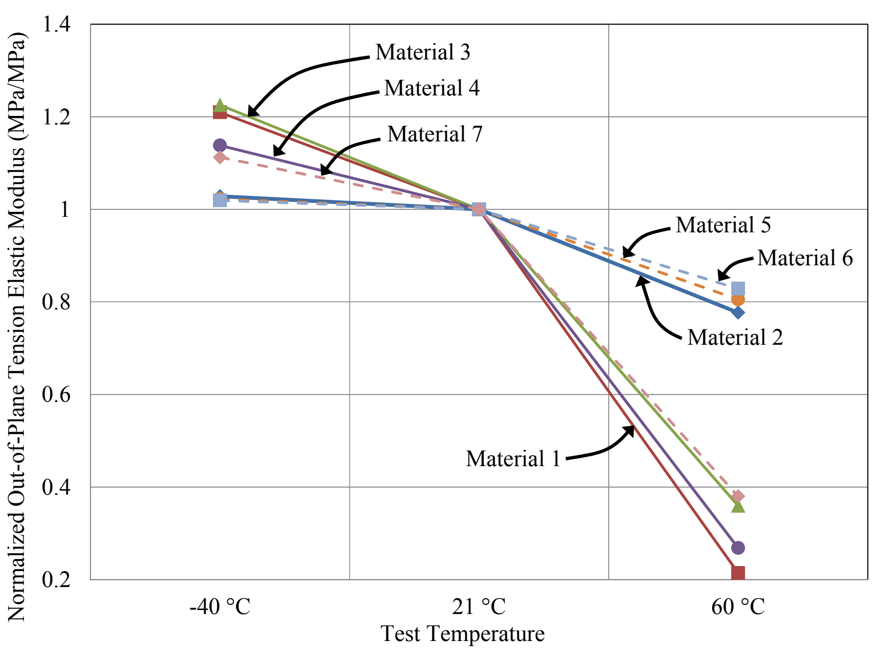

Figure 4. Effects of Temperature on Out-of-Plane Tensile Elastic Modulus (E_z)

The influence of temperature on the out-of-plane shear modulus (G_{xz}, G_{yz}) was similar to that for the out-of-plane tensile modulus. At a temperature of 60 °C, the out-of-plane shear modulus of materials with API SC-15 epoxy is within 25% that at ambient and decreases by as much as 75% for materials with Huntsman PU Rencast 6405. Temperature does not have as much of an influence on the out-of-plane compressive elastic modulus (EC_z). For all materials, the results indicate that the out-of-plane compressive modulus decreases by no more than 20% at 60 °C.

The results indicate that the in-plane Poisson's ratio (νC_{xy}, ν_{xy}) (under compressive and tensile load) is not directly influenced by the test temperature. Usually, the in-plane Poisson's ratio decreases with a decrease in temperature. However, there are several exceptions identified in the results. The in-plane Poisson's ratio results at hot and cold temperatures are usually within 20% of that at ambient temperatures. Under tensile load and for four materials, the Poisson's ratio increases by more than 20% at a temperature of 60 °C.

The results indicate that the test temperature does not have a direct influence on the out-of-plane Poisson's ratio results. The results at hot and cold temperatures are within 59% to 131% of that at ambient temperatures. The results appear random indicating imperfections in measuring this property for composite materials.

5. Thickness Effects

This section discusses the influence of the composite material thickness on the material testing results. Materials with different thicknesses and the same fiber and resin composition are compared. Therefore, the results of Materials 1, 3, and 4 are compared and the results of Materials 2, 5, and 6 are compared. For the figures presented in this section, average values obtained from the three test temperatures are used and all results have been normalized to the results obtained using a material thickness of 2.54 cm.

Figure 5 shows all normalized strength results for Materials 2, 5, and 6. All three of these materials have material compositions of API SC-15 epoxy and S-2 glass. In Figure 5, a 3.81 cm. thickness represents the normalized results of Material 2, a 2.54 cm. thickness represents Material 5, and a 1.91 cm. thickness represents Material 6. Since all results are normalized to the results obtained with a material thickness of 2.54 cm., the value is always 1.0 for Material 5.

Figure 5 indicates that material thickness has a negligible influence on the strength results. The normalized strength results are always within 0.89 and 1.18 with the exception of the out-of-plane tensile strength. The in-plane strengths decrease slightly and the out-of-plane strengths increase slightly when the material thickness decreases from 2.54 cm. to 1.91 cm. However, these trends are inconsistent when the material thickness decreases from 3.81 cm. to 2.54 cm. The results indicate that the slight variations in material strengths are more dependent on the quality of the composite plate when fabricated and are not influenced by material thickness.

The resulting out-of-plane tensile strength for Material 5 is much lower than any material tested. The results were consistent for all 15 specimens tested (5 at each temperature). The research team was not able to identify any discrepancies in the failure mechanism for Material 5 in comparison to other materials such as Materials 2 and 6. Figure 6 shows out-of-plane tension specimens right after failure for Material 5 and Material 2. Both of these specimens were tested at a temperature of 21°C. The research team was not able to identify any discrepancies during the manufacturing of the plate. Replacement tests were considered since the result was an outlier.

However, since the research team retrieved reliable data for Materials 2 and 6 and since the composite thickness was usually not a critical parameter in the design strength; no more tests were deemed necessary. The out-of-plane stiffness of Material 5 was comparable to Materials 2 and 6. The research team identified the out-of-plane tensile strength of Material 5 as an outlier but also as an example to illustrate how critical the manufacturing procedure is for ensuring the desired strength is achieved.

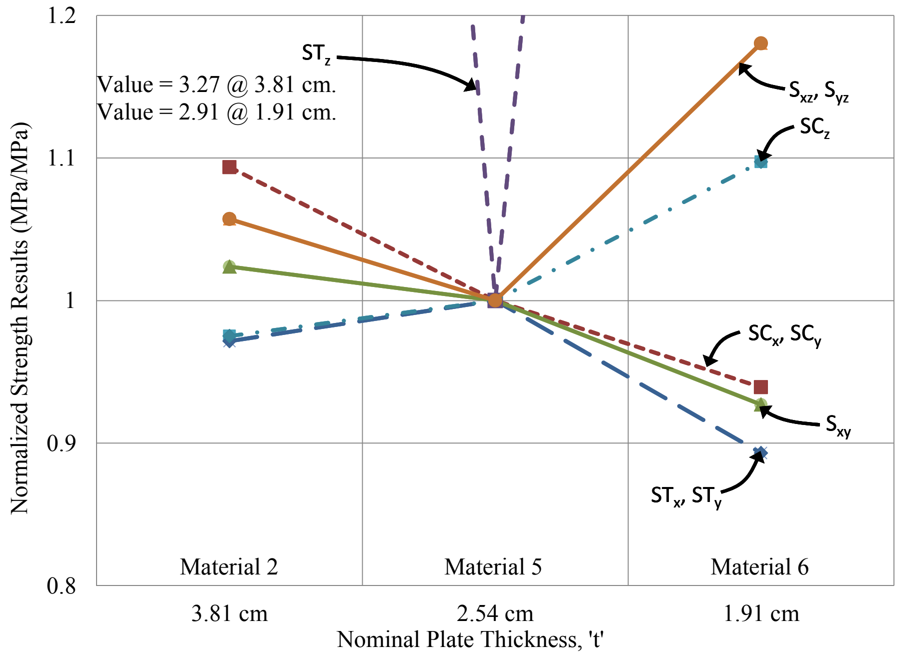

Figure 5. Influence of Composite Thickness on Material Strength (SC-15 Materials)

a) Material 5 b) Material 2

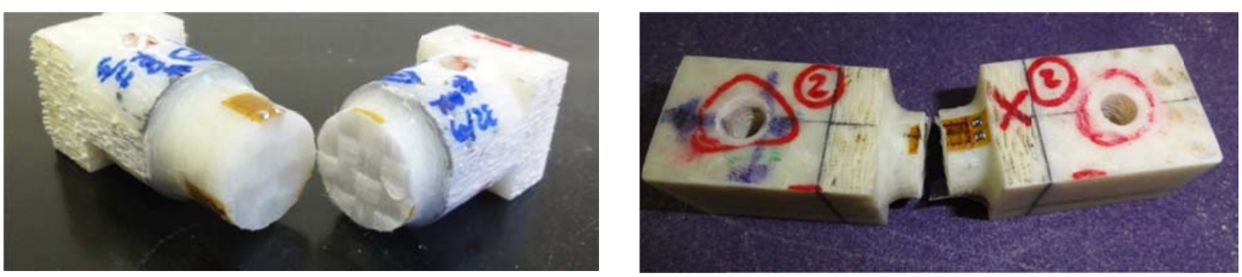

Figure 6. Fracture Out-of-Plane Tension Specimesns Tested at 21 °C

The influence of material thickness on the in-plane and out-of-plane strengths of composites with Huntsman PU Rencast 6405 was also found to be negligible. The results of Materials 1 and 4 (thickness of 2.81 cm. and 1.91 cm., respectively) were very similar to the results of Material 3 (thickness of 2.54 cm.).

Figure 7 shows all normalized stiffness results for Material 2, Material 5, and 6. The results indicate that material thickness does not have an influence on the stiffness results. The out-of-plane shear strength modulus for Material 6 was uncharacteristically low for an unknown reason.

For other stiffness properties, the results of Materials 2 and 6 were within 20% of the results of Material 5. The results increase slightly when the material thickness decreases from 3.81 cm. to 2.54 cm. and decrease slightly when the material thickness decreases from 2.54 cm. to 1.91 cm. Therefore, there is no direct relationship between material thickness and the stiffness results. The results appear to be more dependent on the quality of the material at fabrication.

The influence of material thickness on the stiffness of composites with Huntsman PU Rencast 6405 was also found to be negligible. With the exception of the out-of-plane shear modulus and the out-of-plane compressive elastic modulus, all results at a material thickness of 3.81 cm. or 1.91 cm. were within 10% of that at 2.54 cm. However, the results indicated that the out-of-plane shear modulus increases with a decrease in material thickness.

Figure 8 shows the normalized Poisson's ratios for Material 2, Material 5, and Material 6. Figure 8 includes individual results for temperatures of -40 °C, 21 °C, and 60 °C. The results show no trends in the in-plane or out-of-plane Poisson's ratios for an increase or decrease in thickness. The resulting Poisson's ratios appear random and all results at a material thickness of 3.81 cm. and 1.91 cm. are within 65%-130% of the values obtained at a material thickness of 2.54 cm. The results were similar when comparing the three materials with Huntsman PU Rencast 6405 and S-2 glass.

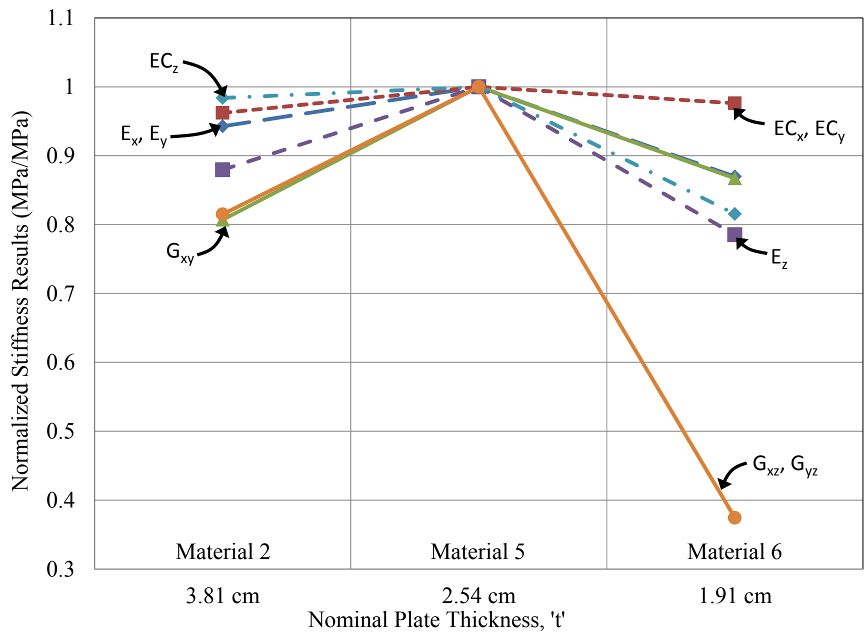

Figure 7. Influence of Composite Thickness on Material Stiffness (SC-15 Materials)

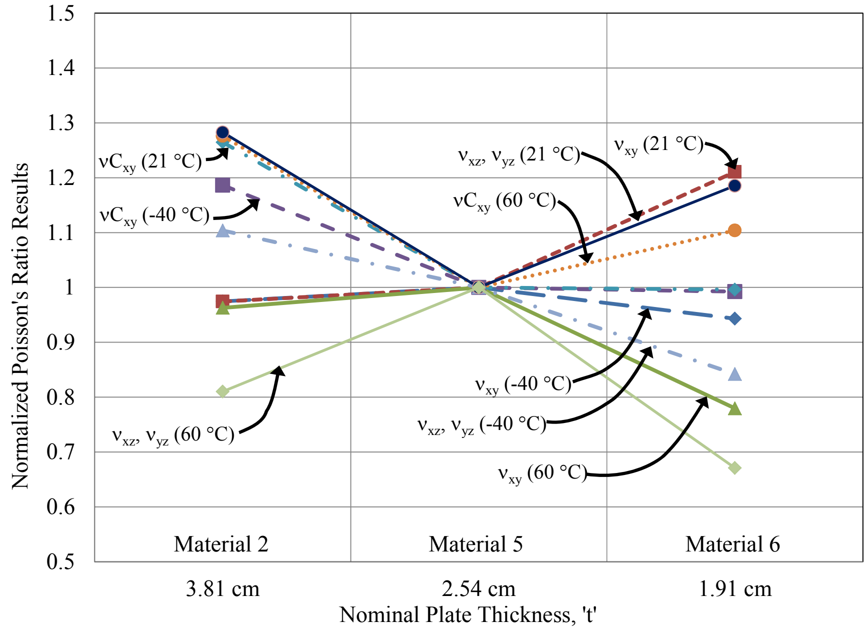

Figure 8 Influence of Composite Thickness on Poisson's Ratio (SC-15 Materials)

6. Material Comparison

This section compares the different material compositions that are included in the research. To limit parameters, the comparisons only include materials that are 1.91 cm. thick. Therefore, the results of Material 1, Material 6, and Material 7 are compared in this section. These materials correspond to Applied Poleramic (API) SC-15 Epoxy with S-2 glass fibers (API SC-15, S2-GLASS), Huntsman PU Rencast 6405 with S-2 glass fibers (RENCAST 6405, S2-GLASS), and Huntsman PU Rencast 6405 with ductile hybrid fabric (RENCAST 6405, DHF), respectively.

The results of all materials tested have been normalized to the results obtained for the material with API SC-15 Epoxy and S-2 glass fibers (Material 6). Two temperatures were chosen for this study; 21 °C and 60 °C. The strength and stiffness results typically increase at a temperature of -40 °C and are therefore less of a concern.

Figure 9 compares the in-plane and out-of-plane strength properties of the three different material compositions. The results indicate that under ambient and elevated temperatures, materials with API SC-15 epoxy are stronger than materials with Huntsman PU Rencast 6405. At ambient temperatures, the normalized results for Material 4 range from 0.95 to 0.66 that of Material 6. API SC-15 epoxy has superior performance over Huntsman PU Rencast 6405 when comparing shear and compressive strengths.

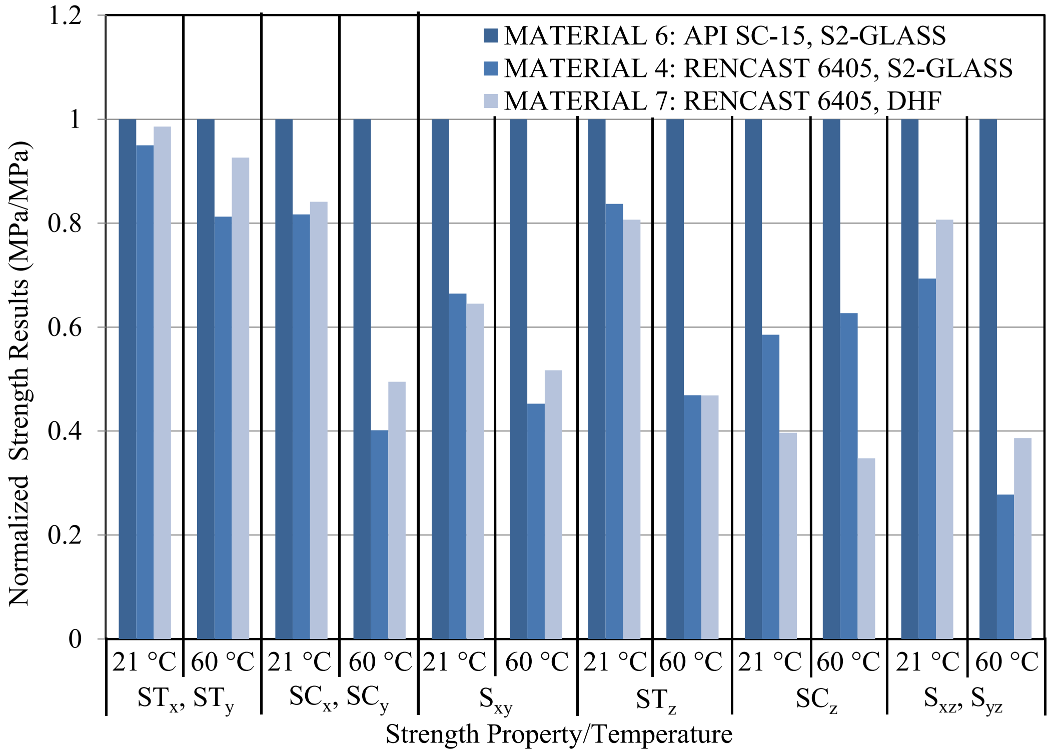

Figure 9. Comparison of Material Strength for Different Materials

Figure 9 reinforces that materials with Huntsman Rencast 6405 are influenced more significantly by temperature than materials with SC-15 epoxy. For example, the in-plane compressive strength of Material 4 is 82% that of Material 6 at a temperature of 21 °C and 40% that of Material 6 at a temperature of 60 °C. The out-of-plane tension strength of Material 4 is 84% that of Material 6 at a temperature of 21 °C and 47% that of Material 6 at a temperature of 60 °C.

Figure 9 indicates that the material with ductile hybrid fabric (Material 7) is usually stronger than the material with the same resin and S-2 glass (Material 4). This result is shown for all properties except in-plane shear strength at a temperature of 21 °C and out-of-plane tensile strength and out-of-plane compressive strength at both temperatures. The material with ductile hybrid fabric is never as strong as the material with API SC-15 epoxy and S-2 glass.

Figure 10 compares the stiffness properties of the three different material compositions. The results indicate that Material 7 has significantly higher in-plane stiffness properties that the other materials tested. This result is attributed to the ultra-high modulus carbon fibers, part of the ductile hybrid fabric. However, Material 6 with API SC-15 epoxy and S-2 glass has the highest out-of-plane stiffness properties. One exception is found in the data.

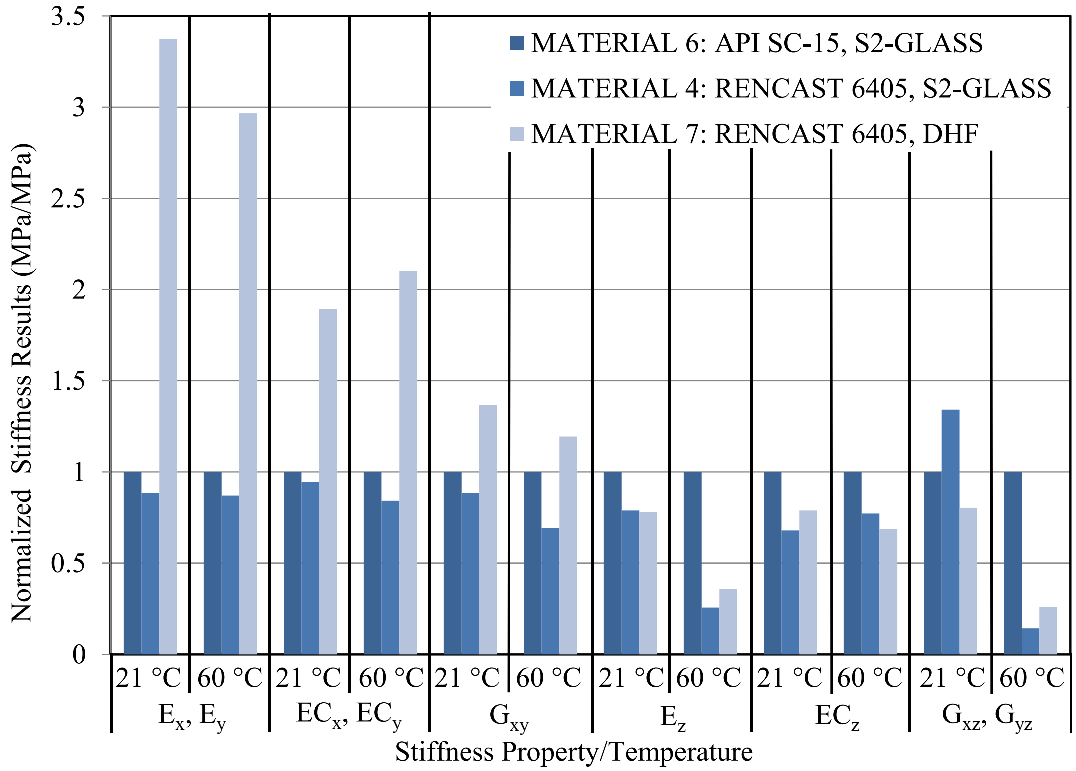

Figure 10. Comparison of Material Stiffness For Different Materials

Figure 10 reinforces that the in-plane stiffness of materials with Huntsman Rencast 6405 is influenced more by temperature than materials with SC-15 epoxy. For example, the in-plane shear modulus of Material 4 is 88% that of Material 6 at a temperature of 21 °C and 69% that of Material 6 at a temperature of 60 °C. Some exceptions were found in the results. Overall, the stiffness of materials with API SC-15 epoxy is more consistent at various temperatures.

7. Statistical Analysis of Results

This section summarizes the statistical significance of the experimental results considering the standard deviations of each individual sample set (results from group of five specimens tested for each material, each test type, and each test temperature). The results of all seven materials at each test temperature were used to perform this study. However, only the out-of-plane strength \ results along with all Poisson's ratio results are shown graphically.

To directly compare the different properties measured in this research, the coefficient of variance (*CV*) was computed for each sample set and presented in this section. This property is defined in Equation 1 were σ is equal to one standard deviation and μ is equal to the mean value:

$$CV = \frac{\sigma}{\mu} * 100\% \qquad (1)$$

For all in-plane strength properties, the *CVs* were found to be relatively low. All results were found to be 16% or less which indicates the data is reliable. The *CVs* were also found to be

relatively low, 18% or less, for in-plane stiffness properties. The *CVs* were found to be higher for in-plane strength and stiffness properties when tests were performed at 60 °C. The in-plane strength and stiffness results of materials with SC-15 epoxy and S-2 glass fibers are usually more reliable than the results of materials with Huntsman PU Rencast 6405.

CVs for out-of-plane strength properties an all Poisson's ratio results are further analyzed using bar charts in Figures 11-12. All three temperatures were considered for this study. The average results for the three materials with Huntsman PU Rencast 6405 and S-2 glass are used for the comparisons and average results for the three materials with API SC-15 Epoxy with S-2 glass are used for the comparisons.

Figure 11 shows the resulting *CVs* that represent the out-of-plane strength properties of the three different material compositions. The results indicate that the out-of-plane compressive strength results are more reliable than the out-of-plane shear results and the out-of-plane tensile results. All out-of-plane compressive strength results are 5% or less. The out-of-plane shear strength results of Material 7 are less reliable than any other out-of-plane strength results. The values are as high as 18% at a test temperature of 60 °C.

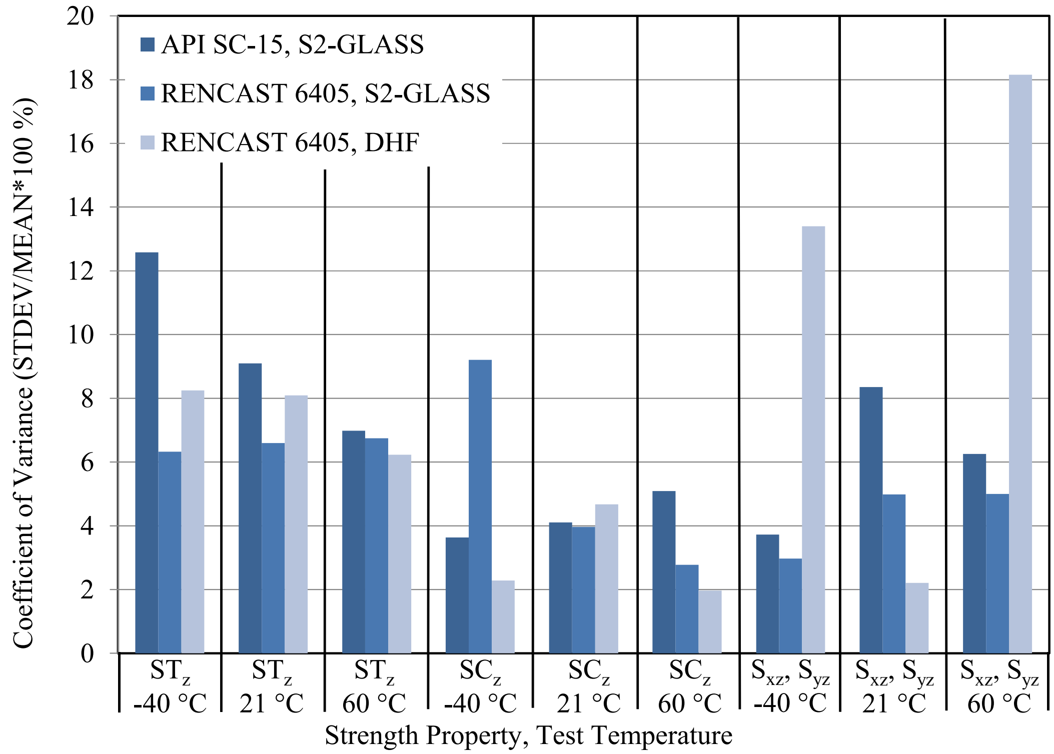

Figure 6: Coefficient of Variance for Out-of-Plane Strength Properties

The *CVs* that represent the out-of-plane stiffness properties of the four different material compositions indicated that the out-of-plane stiffness results are less statistically significant at a test temperature of 60 °C. There were no other notable trends found in the data. All results were less than 15% with the exception of the out-of-plane tension modulus and the out-of-plane shear modulus for Material 7 at a test temperature of 60 °C.

Figure 12 shows the resulting *CVs* that represent the Poisson's ratio results for the three different material compositions. The results indicate that the in-plane Poisson's ratio results have high *CVs*. Higher *CVs* are often found for materials tested at a test temperature of 60 °C. The out-of-plane Poisson's results are more reliable than the in-plane Poisson's results. However, when performing the out-of-plane Poisson's test, the test is focused on achieving a mean Poisson's ratio using a set of relatively consistent data. The in-plane tests focus on the in-plane strength and stiffness properties and not particularly on the Poisson's ratio. The material with Ductile Hybrid Fabric often resulted in the highest *CVs*. The materials with Huntsman PU Rencast 6405 and S-2 glass have the highest *CVs* when subjected to tensile stresses. The Poisson's ratio results are most reliable for materials with API SC-15 epoxy and S-2 glass fibers. Overall, the Poisson's ratio results are less reliable than the strength and stiffness results.

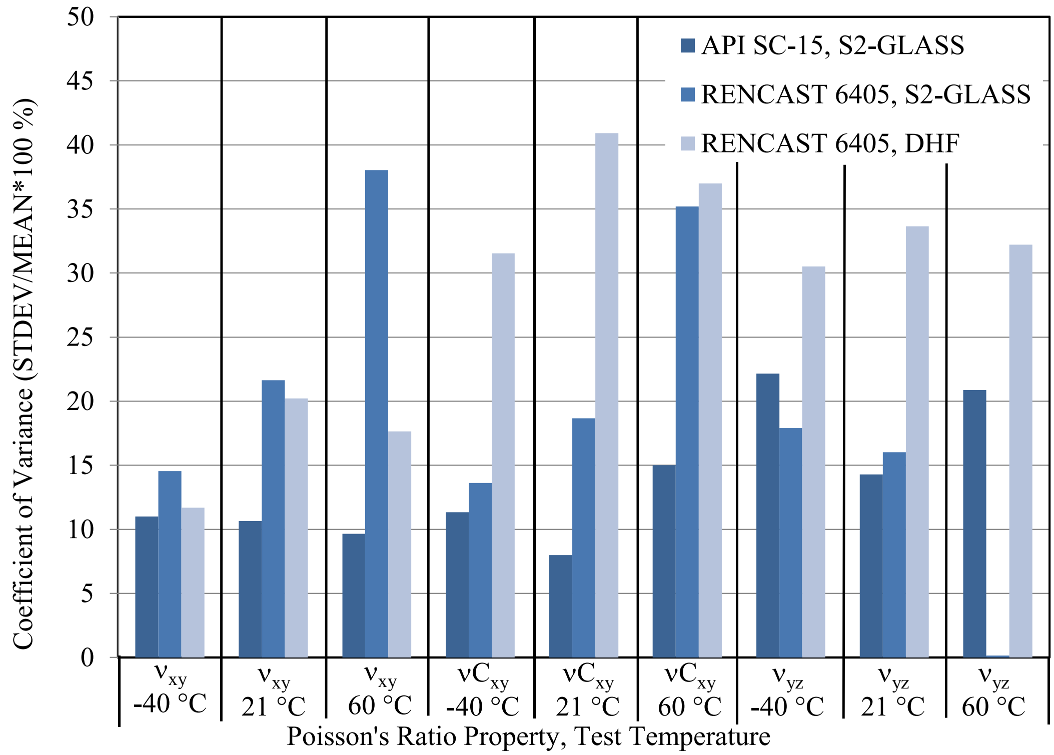

Figure 7: Coefficient of Variance for Poisson's Ratio Results

8. CONCLUSIONS

The primary conclusions from the experimental results presented in this research are as follows:

- The materials with API INSC-15 epoxy and S-2 glass fibers usually have higher in-plane and out-of-plane strength results than materials with Huntsman PU Rencast 6405.
- The material with ductile hybrid fabric usually results in slightly higher strengths than the equivalent material (same resin) with S-2 glass fibers.
- The material with ductile hybrid fabric has a significantly higher in-plane tension elastic modulus than any other material tested due to the ultra-high modulus carbon fibers. It also has the highest in-plane shear modulus and in-plane compressive modulus.

- The out-of-plane stiffness properties of materials with API SC-15 epoxy are usually higher than the out-of-plane stiffness properties of materials with Huntsman PU Rencast 6405.
- The nominal material thickness of the composite plate has no clear influence on the in-plane and out-of-plane material properties of composite materials.
- The in-plane tensile strength, compressive strength, and shear strength increase with a decrease in temperature. The strength results of materials with Huntsman PolyUrethane (PU) Rencast 6405 are more influenced by temperature than materials with API SC-15 Epoxy.
- The out-of-plane tensile strength, shear strength, and compressive strength of composite materials decrease with an increase in temperature. Usually, the out-of-plane strengths of materials with Huntsman PolyUrethane (PU) Rencast 6405 are more influenced by temperature than materials with API SC-15 Epoxy.
- The in-plane stiffness results are not as influenced by temperature as the in-plane strength results as the results at -40 °C and 60 °C are usually within 20% that at ambient temperatures.
- The out-of-plane tensile modulus and out-of-plane shear modulus of composite materials decrease with an increase in temperature. The comparisons are more significant for materials with Huntsman PU Rencast 6405.
- The in-plane and out-of-plane Poisson's ratio results do not appear to be directly influenced by the test temperature or the material composition.
- Significant variation exists in the out-of-plane Poisson's ratio results for Material 7. The ν_{yz} results are significantly higher than the ν_{xz} results.
- The coefficient of variances for all in-plane and out-of-plane stiffness and strength properties are usually lower than 20% for all materials tested.
- The coefficient of variance is usually higher when testing a sample of specimens at a temperature of 60 °C.
- The coefficients of variance for the in-plane and out-of-plane Poisson's ratios are often higher than that obtained for strength and stiffness. The coefficient of variance ranges from 8% to 41% and are typically higher for materials with Huntsman PU Rencast 6405.
- The out-of-plane Poisson's ratio results are more reliable than the in-plane Poisson's results.

9. ACKNOWLEDGEMENT

This material is based upon work supported by the U.S. Army TACOM Life Cycle Command under Contract No. W56HZV-08-C-0236, Work Directive (WD) 00017, through a subcontract with Mississippi State University, and under Contract No. W56HZV-09-C-L550. This work was performed for the Simulation Based Reliability and Safety (SimBRS) research program.

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